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Large-x d/u Ratio in W-boson Production

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Abstract

Recent analysis of proton and deuteron deep-inelastic scattering data have suggested that the extracted d/u quark distribution ratio at large x may be significantly larger than previously believed, if the data are corrected for nuclear binding effects in the deuteron. We examine the sensitivity to the large-x d/u ratio of lepton asymmetries from W-boson production in $p\overline{p}$ and pp collisions at large rapidity, which do not suffer from nuclear contamination.

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In recent years our knowledge of quark distributions in the nucleon has increased significantly, thanks to the accumulation of high-quality deep-inelastic lepton–proton and lepton–deuteron scattering data extending over a large range of Bjorken-x and Q^2. Attention has been focussed primarily on unraveling the detailed structure of the nucleon sea at $x \lesssim 0.1$. The $\overline{u} - \overline{d}$ asymmetry [1], for example, has been carefully probed by the New Muon and NA51 Collaborations at CERN [2], and more recently the CCFR Collaboration [3] has investigated the possibility that the strange and antistrange quark distributions in the nucleon could be different [4].

It has usually been taken for granted, on the other hand, that the structure of the valence quarks in the nucleon is well known and uncontroversial. Unlike for the sea quarks, charge and baryon number conservation fix the first moments of the valence distributions, so that the physics of these is contained entirely in the shapes of their x-distributions. Nevertheless, the precise x-dependence of the u and d quark distributions is rather important from the point of view of understanding spin-flavor symmetry breaking in the proton. Although the simple spin-flavor SU(2)$\times$SU(2) symmetric expectation of $u(x) = 2d(x)$ is clearly violated at large x [5], the limiting behavior of d/u as $x \to 1$ is very sensitive to the dynamics underlying the symmetry breaking mechanism [6].

The softening of the valence d quark distribution relative to the u was correlated by Close [7] with the N–Δ mass splitting, through the observation that both phenomena could be attributed to a larger mass for the spectator qq pair with spin 1 compared with a scalar qq pair. Such a mass shift can be produced for example by pion exchange, instantons, or by a color-magnetic force [8]. In the extreme limit of the scalar qq configuration being the only one relevant at $x = 1$, the d/u ratio would be zero. However, in a model of SU(2)$\times$SU(2) breaking based on a perturbative treatment of one gluon exchange between the spectator quarks [9], the dominant qq configurations at large x were found to be those with spin projection zero, so that the interacting quark carries the helicity of the proton, leading to the prediction $d/u \to 1/5$.

Experimental information on d/u at large x has usually come from measurements of the

F_2^n/F_2^p structure function ratio, with the neutron structure function F_2^n extracted from F_2^p and the deuteron F_2^D structure functions [10–12]. Early analyses suggested that the d/u ratio could be fitted as $d/u = 0.57(1-x)$ [13]. However, typical analyses of deep-inelastic deuteron data have usually been performed under the assumption that the deuteron is a system of two free nucleons moving with some Fermi momentum. While this assumption is perfectly adequate at small and intermediate values of x, at large x ($x \gtrsim 0.7$) the effects of nuclear binding, in addition to nucleon Fermi motion, can significantly alter the extracted d/u ratio [14,15]. In particular, the analysis in Ref. [6] suggested that inclusion of the EMC effect in the deuteron can raise the asymptotic value of d/u from the traditional zero result [13] to a value broadly consistent with the perturbative QCD expectation of 1/5 [9].

In Fig.1 we illustrate the sensitivity of the d/u ratio to the treatment of the nuclear effects in the deuteron. The full (open) circles are derived from the SLAC data [10,11] assuming Fermi motion plus binding (Fermi motion only) corrections [6]. The dashed curves represent the valence d/u ratio as given by standard parameterizations of global parton distributions in Ref. [16] (the results for other parameterizations [17,18] are in fact very similar). Because the large-x d/u ratio in the standard parameterizations [16–18] is fitted to the proton and "neutron" structure function data, obtained from F_2^p and F_2^D without inclusion of nuclear EMC corrections in the deuteron [10,12], the d/u ratio is seen to approach zero as $x \to 1$. To allow for the possibility that the $x \to 1$ limit of d/u is non-zero, we modify the d quark distribution according to:

$$\frac{d(x,Q^2)}{u(x,Q^2)} \to \frac{d(x,Q^2)}{u(x,Q^2)} + \Delta(x,Q^2). \tag{1}$$

The analysis of Ref. [6] suggested that at $Q^2 \approx 10$ GeV^2 the correction term could be parameterized by the simple form:

$$\Delta(x,Q^2 = 10\mathrm{GeV}^2) \approx 0.2\ x^2\ \exp(-(1-x)^2), \tag{2}$$

so that $\Delta \to 1/5$ in the limit $x \to 1$ [9]. (The overall normalization of the valence d quark distribution can be preserved by a correspondingly small change at small x, however, such

a change will hardly be noticeable in the final cross section ratio.) The result with the modified d quark distribution is shown by the solid curves in Fig.1. The effect of evolution on the d/u ratio, though sizable at low x values, is quite small at large x, as seen by evolving [19] the curves in Fig.1 from $Q^2 = 10$ GeV^2 to $Q^2 = M_W^2$.

Given the sensitivity of the d/u ratio obtained from the proton and deuteron data to theoretical inputs for the deuteron structure, to resolve the issue one would obviously like to appeal to data without the need to model the nuclear effects in the deuteron. One such possibility is neutrino and antineutrino scattering from the proton. Because the νp structure function at large x is determined essentially by the d quark distribution, while the $\overline{\nu} p$ by the u distribution, combining the two sets allows one to obtain a model-independent determination of F_2^n/F_2^p in the valence quark dominated region. Unfortunately, the existing neutrino data [20] do not extend to very large x ($x \lesssim 0.6$), and the error bars are too large to discriminate between the different d/u behaviors. Yet another possibility to reduce the sensitivity to nuclear effects is to perform semi-inclusive measurements on the deuteron, tagging a proton in the final state [21]. If the momentum of the produced proton is small, one can probe nearly on-shell neutrons, although the required energy in such experiments must be sufficiently large to obtain a clean separation of the current and target fragmentation regions. final state interactions.

In this paper we investigate the possibility of pinning down the large-x d/u ratio through W-boson production in $p\overline{p}$ and pp collisions. As noted by Berger et al. [22] (see also [23]), this method has the virtue that it is completely free of the theoretical ambiguities associated with modeling the nuclear physics in the deuteron [6,10,11,14,21]. An additional advantage, which has not been discussed previously, is that one does not need to rely on any assumptions about charge symmetry in the nucleon. Some recent model calculations [24] of quark distributions in the proton and neutron have suggested potentially non-negligible charge symmetry breaking effects, which would further contaminate the d/u ratio extracted from H and D data.

Because W^+ and W^- bosons couple to different quark flavors in the proton, any differ-

ences between u and d quark distributions will be reflected through different $W^{\pm}$ rapidity distributions. This property has previously been suggested as a means of constraining the $\overline{d}/\overline{u}$ ratio at small x [22,23,25,26]. In fact the CDF Collaboration at Fermilab [27,28] has measured the lepton charge asymmetry resulting from the decay $W \to l\nu$ (where $l = e, \mu$), although in the rapidity range considered, these data were sensitive mostly to the quark distributions at $x \lesssim 0.3$, which unfortunately is too low to discriminate between the different large-x valence d/u behaviors. By considering charge asymmetries at large lepton rapidities, corresponding to highly energetic decay leptons, we will show that one can probe the valence u and d distributions also in the large-x region where SU(2)×SU(2) symmetry breaking effects are dominant.

At leading order, the differential cross section for the production of a W boson in a proton–h collision (where the hadron $h = \overline{p}$ or p) is proportional to [29]:

$$\frac{d\sigma}{dx_F}(W^+) = K\frac{2\pi G_F}{3\sqrt{2}}\left(\frac{x_1 x_2}{x_1+x_2}\right)\Big\{\cos^2\theta_c\ \Big(u_p(x_1)\,\overline{d}_h(x_2)\ +\ \overline{d}_p(x_1)\,u_h(x_2)\Big) + \sin^2\theta_c\ \left(u_p(x_1)\,\overline{s}_h(x_2)\ +\ \overline{s}_p(x_1)\,u_h(x_2)\right)\Big\}, \tag{3a}$$

where $x_F \equiv x_1 - x_2$. With this definition of x_1 and x_2, positive x_F is defined along the direction of the proton. Furthermore, $x_1 x_2 = M_W^2/s$, where s is the total p–h center of mass energy squared, and M_W is the W-boson mass. (The variable x_F is related to the W-boson rapidity y by $x_F = (M_W/\sqrt{s})(e^y - e^{-y})$). In Eq.(3a) G_F is the Fermi coupling constant, θ_c the Cabibbo angle, and the factor K contains QCD radiative corrections. Similarly one can write the W^- differential cross section as:

$$\frac{d\sigma}{dx_F}(W^-) = K\frac{2\pi G_F}{3\sqrt{2}}\left(\frac{x_1 x_2}{x_1+x_2}\right)\Big\{\cos^2\theta_c\ \left(d_p(x_1)\,\overline{u}_h(x_2)\ +\ \overline{u}_p(x_1)\,d_h(x_2)\right) + \sin^2\theta_c\ \left(s_p(x_1)\,\overline{u}_h(x_2)\ +\ \overline{u}_p(x_1)\,s_h(x_2)\right)\Big\}. \tag{3b}$$

Taking the ratio of the W^+ and W^- cross sections for p–h scattering (c.f. the ratio constructed by Berger et al. [22] in terms of an asymmetry between W^+ and W^- cross sections), one can then define:

$$R_{ph}(x_F) \equiv \frac{d\sigma/dx_F\ (W^+)}{d\sigma/dx_F\ (W^-)}. \tag{4}$$

Production of W-bosons in $p\overline{p}$ collisions has been studied by the CDF Collaboration [27,28,30] at the Tevatron, where the total center of mass energy is $\sqrt{s} = 1.8$ TeV. One can see how $R_{p\overline{p}}$ is related to the d/u ratio by neglecting the small sea-sea and $\sin^2\theta_c$ terms in Eqs.(3), in which case:

$$R_{p\overline{p}}(x_F) \approx \frac{u(x_1)}{d(x_1)} \cdot \frac{d(x_2)}{u(x_2)}, \tag{5}$$

where we have used $\overline{q}_{\overline{p}}(x) = q_p(x)$ to relate all distributions to those in the proton. To date the CDF Collaboration, and most theoretical interest, has focused on constraining quark densities in the small-x region ($x \lesssim 0.3$). To probe the u/d ratio in the proton at large x_1 requires large values of x_F (or equivalently large W-boson rapidities y). For $x_1 \gtrsim 0.5$, a center of mass energy $\sqrt{s} = 1.8$ TeV implies $x_2 \lesssim 0.004$, so that $x_F \approx x_1$.

In order to demonstrate the sensitivity of the ratio of the W^+ to W^- cross sections to d/u at large x, in Fig.2(a) we compare $R_{p\overline{p}}$ for the two different parameterizations of the d-quark distribution used in Fig.1. Evolving the u and the modified and unmodified d quark distributions to the W-boson scale, one can extract from Eq.(1) the correction $\Delta(x, Q^2)$ at $Q^2 = M_W^2$, which to a good approximation can be parameterized as:

$$\Delta(x, Q^2 = M_W^2) \approx 0.18\ x^{1.2}\ \exp\left(-(1-x)^2\right). \tag{6}$$

The ratio $R_{p\overline{p}}$ with the modifed and unmodified d quark distributions is shown by the solid and dashed curves in Fig.2(a) (in the numerical calculations the full expressions from Eqs.(3) are used). As can be seen, the modified distribution already introduces a reduction in the ratio of $\sim 30\%$ at $x_F = 0.6$, and more than 50% for $x_F \gtrsim 0.7$. Indeed, if one allows $d/u \to 0$, the ratio $R_{p\overline{p}}$, which depends on $u(x_1)/d(x_1)$, increases quite dramatically as $x \to 1$.

Of course measurement of this ratio at these rather large values of x_F will be difficult in view of the falling cross sections there. However, by increasing the luminosity and rapidity coverage anticipated in future runs at CDF [31], one should be able to access this region with reasonable statistics. In addition, the statistics can be improved by a factor of two by combining data from $x_F > 0$ with those from $x_F < 0$, since the ratio is inversely symmetric about $x_F = 0$, i.e. $R_{p\overline{p}}(x_F) = 1/R_{p\overline{p}}(-x_F)$.

The large-x d/u ratio can also be probed in pp collisions, for example in future at RHIC. This is again evident by dropping the Cabibbo angle suppressed terms in Eqs.(3) (with $h = p$), so that the ratio R_{pp} of the W^+/W^- cross sections can be approximated by:

$$R_{pp}(x_F) \approx \frac{u(x_1)\ \overline{d}(x_2) + \overline{d}(x_1)\ u(x_2)}{\overline{u}(x_1)\ d(x_2) + d(x_1)\ \overline{u}(x_2)}. \tag{7}$$

Doncheski et al. [32] have recently studied W-boson asymmetries at RHIC energies as a means of determining $\overline{d} - \overline{u}$ differences in connection with the Gottfried sum rule, as well as $\Delta u - \Delta d$ differences in polarized parton distributions. As with the earlier $p\overline{p}$ studies at CDF, however, attention has been focussed exclusively on the sea quark distributions in the small-x region. In contrast, here we point out that RHIC pp collisions can also be used to obtain information on the valence quark distributions at large x. It was also suggested in Ref. [33] that one could measure the ratio $\Delta d/d$ at large x in polarized $p\vec{p}$ collisions at RHIC, however, in view of the present discussion it is clear that the unpolarized d quark distribution itself needs to be accurately determined before any conclusions can be drawn about Δd.

For a RHIC center of mass energy $\sqrt{s} = 500$ GeV, for $x_1 \gtrsim 0.6$ at large x_F one will have $x_2 \lesssim 0.04 \ll x_1$, so that one may expect for the antiquark distributions $\overline{u}(x_1) \ll \overline{u}(x_2)$ and $\overline{d}(x_1) \ll \overline{d}(x_2)$, in which case R_{pp} will directly probe the valence u/d ratio:

$$R_{pp}(x_F) \approx \frac{u(x_1)}{d(x_1)} \cdot \frac{\overline{d}(x_2)}{\overline{u}(x_2)}, \qquad x_1 \gg x_2. \tag{8}$$

In Fig.2(b) we compare the ratio $R_{pp}(x_F)$ for the standard CTEQ parameterization [16] (dotted curve) with that calculated with the modified d distribution in Eq.(1) (solid curve). As for the $p\overline{p}$ case, the latter is significantly smaller for $x_F \gtrsim 0.5$ than the ratio with the standard parameterization. We emphasize that these effects are considerably larger than those found in earlier analyses [22] by comparing standard parton parameterizations.

Although the differences between the x_F ratios with the unmodified and modified distributions for both $p\overline{p}$ and pp collisions are quite conspicuous at large x_F, in practice it is not the x_F distributions which are measured but rather the charge asymmetry of the leptons

resulting from the $V{-}A$ decay of the W bosons. The measured lepton asymmetry is defined by [34]:

$$A(y_l) = \frac{d\sigma/dy_l(l^+) \; - \; d\sigma/dy_l(l^-)}{d\sigma/dy_l(l^+) \; + \; d\sigma/dy_l(l^-)}, \tag{9}$$

where the lepton rapidity $y_l = 1/2 \ln\left[(E_l + p_l)/(E_l - p_l)\right]$ is defined in terms of the decay lepton's energy E_l and longitudinal momentum p_l in the laboratory frame. The differential cross section $d\sigma/dy_l$ is obtained by convoluting the $q\overline{q} \to W$ cross section for each x_F with the relevant $W \to l\ \nu$ decay distribution, $d\sigma/d\cos\theta \propto (1 \pm \cos\theta)^2$, where θ is the angle between the lepton $l^\pm$ direction and the $W^\pm$ polarization in the W rest frame.

In Fig.3 we show the lepton asymmetry $A(y_l)$ calculated for the standard CTEQ parton parameterization [16] (dotted) and with the modified d quark distribution, Eq.(1), (solid). The asymmetry for $y_l < 0$ is equal and opposite to that for positive y_l. To compare with the CDF lepton asymmetry data [27,28] we have made a cut in the transverse energy of the lepton of $E_T > 25$ GeV in Fig.3(a). With this cut the x_F distributions at large x_F, which are relatively small in magnitude, are overwhelmed by the much larger cross sections at smaller x_F, where the unmodified and modified distributions are essentially equivalent. In order to resolve the differences at large x_F in the y_l distributions one should select from the lepton spectrum only the most highly energetic events. In practice, for the CDF center of mass energy $\sqrt{s} = 1.8$ TeV, this requires a tighter cut of $E_T \gtrsim 35$ GeV on the transverse lepton energy. Such a cut favors the large-x_F distributions, so that for large lepton rapidities ($y_l \gtrsim 2$) the differences between valence quark distributions at large x_1 will leave quite noticeable traces, Fig.3(b). Note that the latest data [28] already extend up to $y_l \approx 2.2$, with quite small error bars even at the largest rapidities. With an upgraded Tevatron, a rapidity coverage of at least up to $y_l = 2.5$ is expected [31], where the effects are of the order of 50%. Together with a luminosity upgrade, this should allow a significant improvement in the statistics so as to pose a serious test for the two scenarios for d/u at large x.

In summary, W-boson asymmetries in pp and $p\overline{p}$ collisions can be used to constrain the behavior of valence quark distributions in the large-x region. The principle advantage

is that one can avoid the theoretical ambiguities associated with the traditional method of extracting quark distributions from proton and deuteron deep-inelastic scattering data, which inevitably requires modeling the nuclear effects in the deuteron. We have investigated the sensitivity of the asymmetries to different asymptotic behaviors of the valence d/u ratio, and find the ratio of W^+/W^- cross sections to be very sensitive to the precise $x \to 1$ dependence of d/u for values of $x_F \gtrsim 0.5$. By measuring of the resulting lepton charge asymmetry at large lepton rapidities one can determine this ratio experimentally by selecting the more energetic decay leptons. The availability of such data from an upgraded Tevatron or RHIC would be instrumental in pinning down the asymptotic behavior of d/u, and therefore should help unravel the physics behind the mechanism of flavor symmetry breaking in the nucleon.

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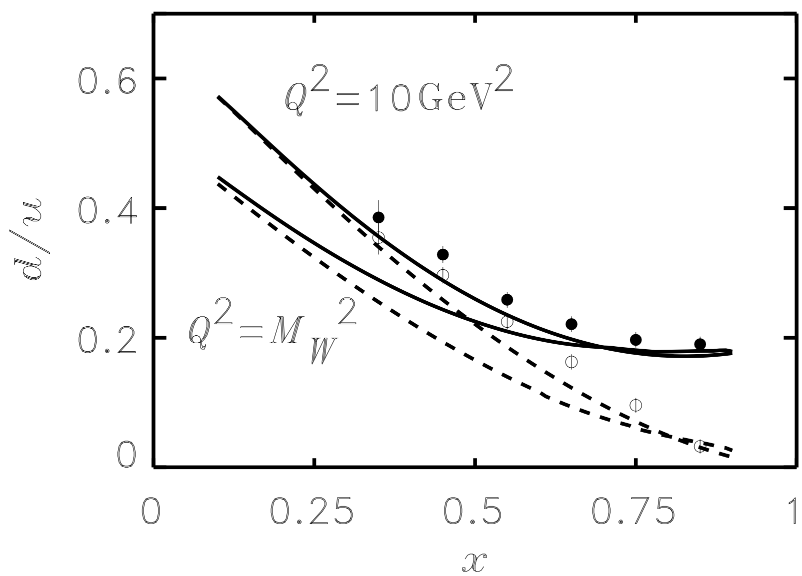


FIG. 1. d/u quark distribution ratio at $Q^2 = 10$ GeV^2 and $Q^2 = M_W^2$. Dashed curves are parameterizations from Ref. [16], solid curves include the modified d quark distribution in Eqs.(1), (2) and (6). Full (open) circles represent SLAC data from Refs. [10,11] analyzed assuming binding plus Fermi motion (Fermi motion only) corrections in the deuteron [6].

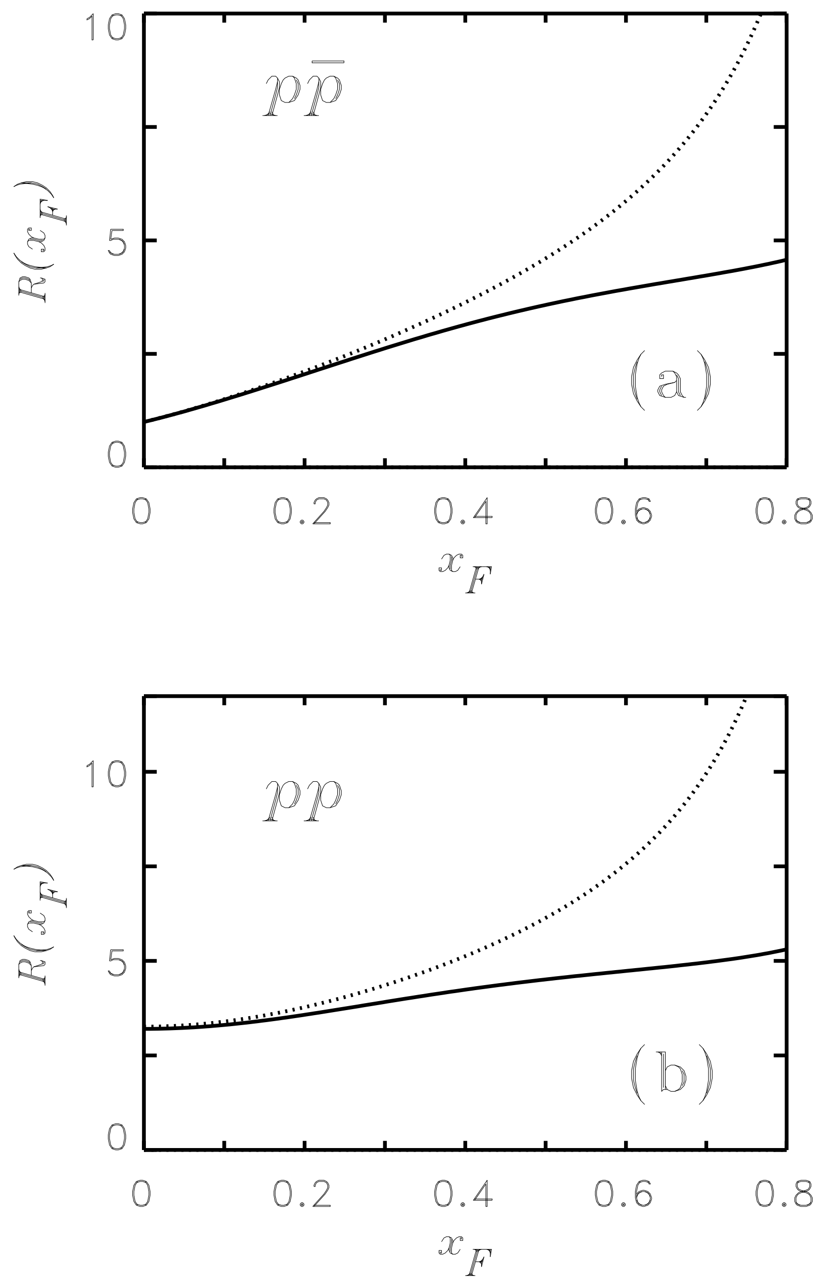
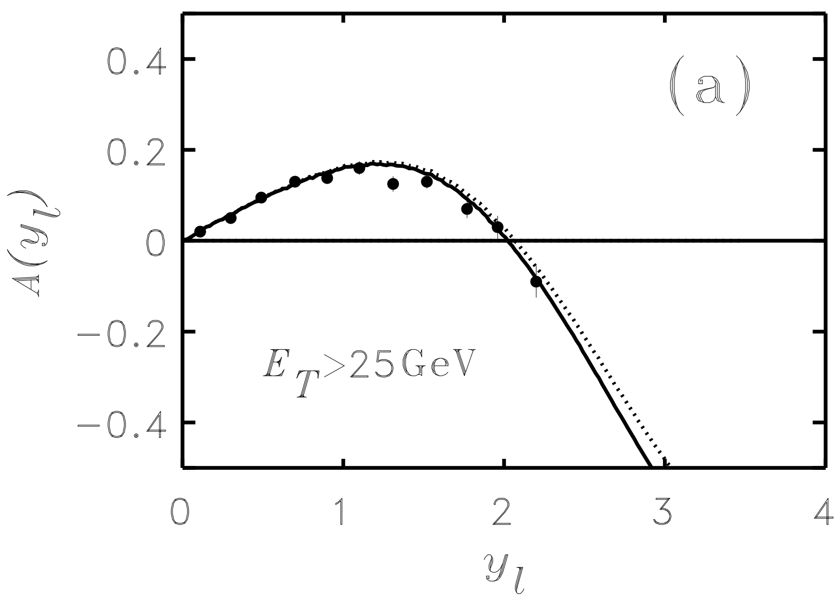


FIG. 2. Ratio of W^+/W^- cross sections as a function of x_F in (a) $p\overline{p}$ collisions at a center of mass energy $\sqrt{s} = 1.8$ TeV, and (b) pp collisions at $\sqrt{s} = 500$ GeV. The results for the standard CTEQ parton parameterization [16] are represented by the dotted curves, while the solid are for the d quark distribution modified according to Eq.(1).



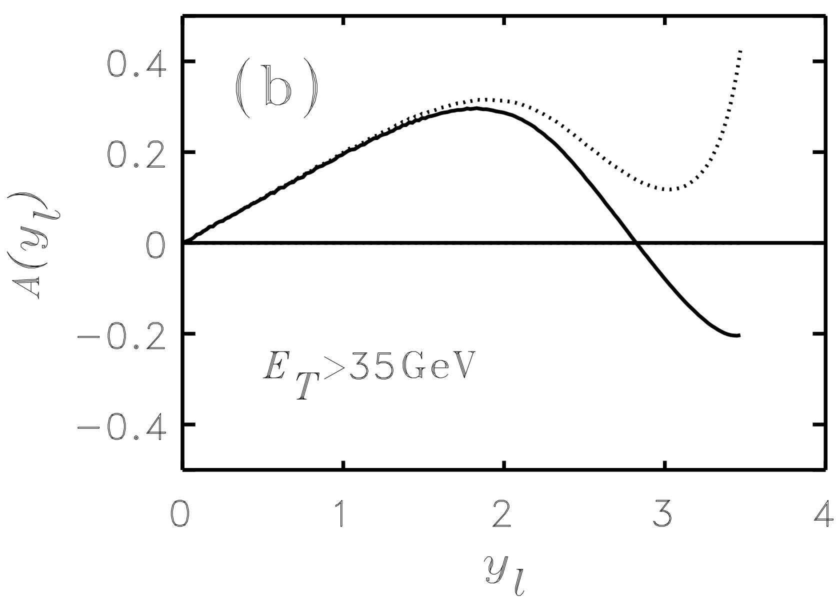


FIG. 3. Lepton charge asymmetry as a function of lepton rapidity y_l in $p\overline{p}$ collisions for $\sqrt{s} = 1.8$ TeV. (a) $E_T > 25$ GeV cut for comparison with data from CDF [27,28]; (b) $E_T > 35$ GeV cut. Solid and dotted curves are as in Fig.2.